A Cognitive Subcarriers Sharing Scheme for OFDM based Decode and Forward Relaying System

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Abstract. This paper analyzes the performance of a proposed subcarriers sharing scheme. According to the scheme, secondary system helps the primary system via two phase Decode and Forward orthogonal frequency division multiplexing based relaying. If primary (licensed user) is unable to achieve its target rate then secondary transmitter (which is located within a critical distance from primary transmitter) will provide few subcarriers to primary receiver, to fulfill the requirement of the primary system and remaining subcarriers can be used by secondary (cognitive) system for its own data transmission. If secondary transmitter is located at or beyond the critical distance from primary transmitter then no spectrum sharing is possible. The analytic expression of outage probability of the primary and secondary system has been computed. Through theoretical and simulation results it has been shown that the primary outage probability with cooperation (while secondary transmitter acts a partial relay) is less than the outage probability for direct transmission. Therefore opportunistic spectrum sharing can be achieved by secondary system.

Key words: OFDM, opportunistic spectrum sharing, cooperative relaying, outage probability

1 Introduction

Due to advent of new wireless communication techniques, the demand for additional bandwidth is increasing every other day. Researchers and technologists are seeking the solutions to cope up with the problem of bandwidth scarcity. Cognitive radio technology introduced by [1] has provided an alternative to solve the problem of spectrum scarcity and under-utilization. Cognitive radio networks support opportunistic spectrum sharing (OSS) [2] via granting secondary system (low priority) to share the spectrum of the primary user (higher priority) to efficiently utilize the radio spectrum. Practical implementation of OSS in Long Term Evolution-Advanced (LTE-A) has been proposed in [3]. According to [3], OSS has played a significant role with carrier aggregation technique to improve the performance of the LTE-A system.

Recently cooperative relaying has been incorporated to facilitate spectrum sharing schemes in cognitive radio system [4]. In cooperative relaying one or more relays are used to improve the performance of a system via space and time diversity. Relay based on Amplify and Forward (AF), Decode and Forward (DF) or Compressed and Forward (CF) protocol [5] acts as a virtual antenna for the primary system.

Cooperative spectrum sharing for single carrier system has been proposed in [6]. In this work, the regenerated primary signal at secondary transmitter is combined with the secondary signal by providing fraction of secondary power to the primary signal and remaining power to the secondary signal. Cooperative relaying for two phase cognitive system has been given in literature [7]. Some existing work on cognitive radio is based on interference limited systems [8] in which primary system has capacity to handle additional interference from other systems without affecting its quality of service. Combination of multi-carrier modulation such as OFDM and DF relaying has been proposed in literature [9] for selective subcarrier pairing and power allocation. In [9] more secondary system power will be provided to the better channel. The optimization of subcarrier power to maximize the cognitive system throughput without providing excessive interference to the primary system has been given in [10]. Similarly, a protocol for OFDM AF relaying has been given in [11]. In this work, a joint optimization problem is formed for subcarrier pairing and power allocation, where secondary system uses fraction of its subcarriers to boost the performance of primary system. Results are shown for outage probability w.r.t secondary system power. However, in [11] authors have not determined the exact numbers of subcarriers relayed via secondary transmitter to primary receiver, to fulfill the target rate requirement of primary system. Another work based on OFDM-AF relaying [12] illustrates that the secondary system can do opportunistic communication by providing half subcarriers to primary receiver to achieve the target rate of primary system and remaining half subcarriers can be used for secondary communications.

In this paper, we have proposed an opportunistic subcarriers sharing scheme based on OFDM-DF relaying. We have computed the outage probability as a performance metrics for primary and secondary systems for different numbers of subcarriers. In this scheme, it is assumed that both primary and secondary system uses OFDM based modulation. According to the scheme, if primary system is not able to achieve the target rate of transmission due to poor link quality then advanced secondary system supports the primary system via converting into a two phase cooperative relaying based on DF protocol. Here secondary transmitter which behaves as a relay for primary system will receive the signal broadcast by primary transmitter over N subcarriers in phase I, decode it, and forward few (D) subcarriers to the primary receiver in phase II in order to satisfy the target rate requirement of primary system. The remaining (N-D) subcarriers can be used by secondary transmitter to transmits its own signal to secondary receiver. Hence secondary system while working as a relay for primary system will get opportunistic spectrum access in exchange of fulfilling the target rate requirement of primary system. The number of subcarriers (D) allocated to the primary system depend on the required target rate or quality of services of the primary system. If primary target rate changes, D also changes.

Primary transmitter (PT) and primary receiver (PR) are the components of the primary system while secondary system comprises of secondary transmitter (ST) and secondary receiver (SR) as shown in figure 1. Here we assume that the secondary system follows the same radio protocol as primary system (eg. source coding, channel coding, synchronization). Results interpret the requirement of subcarriers relayed via ST to PR to fulfill the target rate of primary system. As numbers of relayed subcarriers increases, primary outage probability decreases while secondary outage probability increases. Outage probability is also a factor of distance between primary system and ST. As discussed later, for a given co-linear model (where PT, ST, PR and SR are co-linear), as distance between secondary transmitter and primary receiver decreases, primary outage probability decreases and less number of subcarriers would be required to forward the primary signal. But at the same time, distance between primary and secondary transmitter increases and decoding of primary signal at ST becomes the limiting factor for outage probability and no more performance improvement will be achieved by increasing the number of subcarriers after a threshold. There will be a critical distance, defined as a distance between PT and ST above which no opportunistic spectrum access is possible. Theoretical and simulation results are provided for outage probability for both primary and secondary system. It has been shown through the results that, as long as ST lies within the critical distance, outage probability of proposed scheme will be less as compare to the direct transmission. Excellent agreement between the theoretical and simulation results validate the analytical results of the proposed scheme.

The remainder of this paper is organized as follows. Section II discusses the system model. Section III demonstrates the rate and outage probability analysis for direct and cooperative communication for both primary and secondary system. Simulation results and discussion are provided in section IV. Section V concludes the paper.

2 System Model

In our system model we consider secondary system as an advance relay with cooperative relaying functionality. OFDM is used as a modulation scheme to modulate primary & secondary signal over N subcarriers. All transmission and reception nodes *i.e.* PT, PR, ST, SR comprise single antenna. Primary system has authority to operate in some license band while secondary system can do only opportunistic spectrum access in the primary license band, when primary is unable to achieve its target rate of communication due to various channel impairments.

Here Rayleigh frequency flat fading model has been considered for primary and secondary system. The channel coefficient corresponds to PT→PR is $\Psi_{1,k}$ over subcarrier $k(1 \leq K \leq N), \Psi_i \sim \mathcal{CN}(0, \zeta_i^{-l})$ where ζ is the normalized distance between transmitter and receiver. Normalization is done w.r.t. distance between PT→PR, which is set to $\zeta = 1$ and path loss component is denoted by l. Similarly channel coefficients for primary to secondary transmitter, secondary transmitter to primary receiver and secondary transmitter to secondary receiver is denoted as $\Psi_{2,k}, \Psi_{3,k}, \Psi_{4,k}$ respectively. The channel instantaneous gain for each subcarrier is defined as $\gamma_{1,k} = |\Psi_{1,k}|^2, \gamma_{2,k} = |\Psi_{2,k}|^2, \gamma_{3,k} = |\Psi_{3,k}|^2$ and $\gamma_{4,k} = |\Psi_{4,k}|^2$. The additive white Guassian noise at each receiver is denoted as $n_{1,k}, n_{2,k}, n_{4,k} \sim \mathcal{CN}(0, \sigma^2)$. The primary and secondary signal is denoted as $s_{p,k}$ and $s_{s,k}$ respectively with zero mean and $E\{s^*_{p,k} s_{p,k}\} = E\{s^*_{s,k} s_{s,k}\} = 1$.

Here total transmission has been divided into two time phases. In phase I, PT will broadcast signal to PR, ST & SR. In phase II, PT remains silent and ST will decode and forward few subcarriers to PR, keeping in mind to fulfill the requirement of primary target rate on top priority. With remaining number of subcarriers ST can do opportunistic spectrum access to transmit its own signal to SR. ST will transmit orthogonal subcarriers to PR & SR to avoid interference between them.

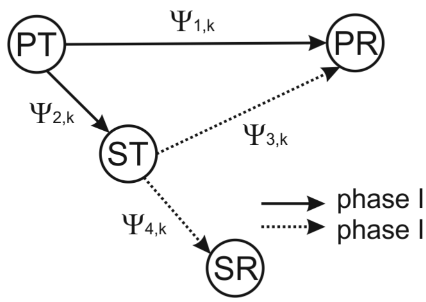

Fig. 1. System model

3 Rate & Outage Analysis for Direct & Cooperation

3.1 Primary outage probability for direct transmission

In phase 1, signal $s_{p,k}$ is broadcast by PT, received by PR and overheard by SR & ST. Received signal at PR over subcarrier k is denoted as $\phi_k^{pr,1}$ which is equal to,

$$\phi_k^{pr,1} = (p_{p,k})^{\frac{1}{2}} \Psi_{1,k} s_{p,k} + n_{1,k} \tag{1}$$

where $n_{1,k}$ denotes AWGN noise over subcarrier k and $p_{p,k}$ is the power of each subcarrier. The total power available at PT is sum of all subcarrier power i.e. $\sum_{k=1}^{N} p_{p,k}$. Let's the available bandwidth at the primary system is divided into N orthogonal subcarriers and primary signals are transmitted over N subcarriers. The instantaneous rate for all N subcarriers is given as,

$$R_N = \sum_{k=1}^{N} \log_2 \left(1 + \frac{p_{p,k}\gamma_{1,k}}{\sigma_1^2}\right). \tag{2}$$

The target rate of primary system is R_T and outage occur if $R_N < R_T$

$$P_{out} = Pr(R_N < R_T) \tag{3}$$

Without any loss of generality, let's assume that all subcarriers comprises same power $p_{p,1} = p_{p,2} = p_{p,N} = p_p$ and channel coefficients of all subcarriers are same for one OFDM symbol $\gamma_{1,1} = \gamma_{1,2} = \gamma_{1,N} = \gamma_1$.
So (2) can be deduce to,

$$R_N = N\log_2\left(1+\frac{p_p\gamma_1}{\sigma_1^2}\right). \tag{4}$$

The outage probability,

$$P_{out} = Pr\left(\gamma_1 < \frac{(2^{R_T/N}-1)\sigma_1^2}{p_p}\right). \tag{5}$$

where $\gamma_1 \sim \exp\left(\zeta_1^l\right)$ is exponentially distributed i.i.d. random variable. So the outage probability for the direct transmission can be deduced to

$$P_{out} = 1-\exp\left(-\frac{\sigma_1^2(2^{R_T/N}-1)\zeta_1^l}{p_p}\right) \tag{6}$$

where ζ_1 is distance between PT and PR and l is path loss component.

3.2 Primary Outage Probability with Cooperation

With cooperation ST behaves as a relay between PT and PR to provide diversity gain to the primary system. ST behaves as a partial relay to decode & forward primary data to primary receiver. It will decode and forward D subcarriers to PR and remaining N-D subcarriers to SR. Signal received by Secondary Transmitter in phase I is

$$\phi_k^{st,1} = (p_{p,k})^{\frac{1}{2}}\Psi_{2,k}s_{p,k} + n_{2,k} \tag{7}$$

where $n_{2,k}$ is the AWGN noise over subcarrier k. The instantaneous rate of signal received at ST with N subcarriers is,

$$R_N^{Pt-St} = \sum_{k=1}^{N}\log_2\left(1+\frac{p_{p,k}\gamma_{2,k}}{\sigma_2^2}\right). \tag{8}$$

Taking same assumption as (2), eq. (8) will be deduce to,

$$R_N^{Pt-St} = \frac{N}{2}\log_2\left(1+\frac{p_p\gamma_2}{\sigma_2^2}\right) \tag{9}$$

where $\frac{1}{2}$ is due to transmission in two phases. Out of total N subcarriers received from PT, ST will decode & forward only D subcarriers to PR while remaining N-D subcarriers will be transmitted to SR. The instantaneous rate at PR after Maximum ratio combining (MRC) of two phases transmission with a condition of successful decoding of primary signal $s_{p,k}$ at ST is,

$$R_{PR}^{MRC} = \frac{1}{2}\sum_{k=1}^{D}\log_2\left(1+\frac{p_{p,k}\gamma_{1,k}}{\sigma_1^2}+\frac{p_{s,k}\gamma_{3,k}}{\sigma_1^2}\right)+\frac{1}{2}\sum_{k=1}^{N-D}\log_2\left(1+\frac{p_{p,k}\gamma_{1,k}}{\sigma_1^2}\right) \tag{10}$$

where factor $\frac{1}{2}$ is due to two phase transmission and $p_{s,k}$ is the power of each subcarrier belonging to secondary system. Let all subcarriers carries same power and channel coefficients of a path are same for all subcarriers *i.e.* $\gamma_{1,1} = \gamma_{1,2} = \gamma_{1,N} = \gamma_1, \gamma_{2,1} = \gamma_{2,2} = \gamma_{2,N} = \gamma_2, \gamma_{3,1} = \gamma_{3,2} = \gamma_{3,N} = \gamma_3$. So (10) can be deduce to,

$$R_{PR}^{MRC} = \frac{D}{2}\log_2\left(1+\frac{p_p\gamma_1}{\sigma_1^2}+\frac{p_s\gamma_3}{\sigma_1^2}\right)+\frac{N-D}{2}\log_2\left(1+\frac{p_p\gamma_1}{\sigma_1^2}\right). \quad (11)$$

On the other hand when ST would unable to decode the primary signal received in phase I of transmission then there will be no transmission from ST to PR in phase II. But PR would still be able to receive the primary signal from direct link. Thus the outage probability is,

$$P_{out}^{p} = Pr(R_N^{Pt-St} > R_T)Pr(R_{PR}^{MRC} < R_T) + Pr(R_N^{Pt-St} < R_T)Pr(\frac{1}{2}R_N < R_T) \quad (12)$$

where R_N can be found from (2).

$$Pr\left(\frac{1}{2}R_N < R_T\right) = Pr\left(\gamma_1 < \frac{\rho_1\sigma^2}{p_p}\right) = 1 - e^{-\frac{\zeta_1^l\sigma^2}{p_p}\rho_1} \quad (13)$$

$$Pr(R_N^{Pt-St} < R_T) = Pr\left(\gamma_2 < \frac{\rho_1\sigma^2}{p_p}\right) = 1 - e^{-\frac{\zeta_2^l\sigma^2}{p_p}\rho_1}. \quad (14)$$

Similarly,

$$Pr(R_N^{Pt-St} > R_T) = Pr\left(\gamma_2 > \frac{\rho_1\sigma^2}{p_p}\right) = e^{-\frac{\zeta_2^l\sigma^2}{p_p}\rho_1} \quad (15)$$

where $\gamma_1 \sim \exp\left(\zeta_1^l\right)$, $\gamma_2 \sim \exp\left(\zeta_2^l\right)$, and $\rho_1 = 2^{\frac{2R_T}{N}-1}$

$$Pr(R_{PR}^{MRC} < R_T)$$
$$= Pr\left(\left(1+\frac{p_p\gamma_1}{\sigma_1^2}+\frac{p_s\gamma_3}{\sigma_1^2}\right)^D\left(1+\frac{p_p\gamma_1}{\sigma_1^2}\right)^{N-D} < 2^{2R_T}\right). \quad (16)$$

Let $\sigma_1^2 = \sigma_2^2 = \sigma_3^2 = \sigma^2$,

$$= Pr\left(\left(1+\frac{p_p\gamma_1}{\sigma^2}+\frac{p_s\gamma_3}{\sigma^2}\right)^D\left(1+\frac{p_p\gamma_1}{\sigma^2}\right)^{N-D} < 2^{2R_T}\right). \quad (17)$$

Let $\frac{p_p\gamma_1}{\sigma^2}+\frac{p_s\gamma_3}{\sigma^2} >> \sigma^2$, Now (17) deduce to

$$= Pr\left(\left(p_p\gamma_1+p_s\gamma_3\right)^D\left(p_p\gamma_1\right)^{N-D} < 2^{2R_T}\sigma^{2N}\right) \quad (18)$$

$$= Pr\left(\left(p_p\gamma_1+p_s\gamma_3\right) < \frac{\left(2^{2R_T}\sigma^{2N}\right)^{\frac{1}{D}}}{\left(p_p\gamma_1\right)^{\frac{N-D}{D}}}\right) \quad (19)$$

$$= Pr\left(\gamma_3 < \frac{\Lambda^{\frac{1}{D}}}{p_s\left(p_p\gamma_1\right)^{\frac{N-D}{D}}} - \frac{p_p\gamma_1}{p_s}\right) \quad (20)$$

where $\Lambda = 2^{2R_T}\sigma^{2N}$

Let's

$$\frac{\Lambda^{\frac{1}{D}}}{p_s\left(p_p\gamma_1\right)^{\frac{N-D}{D}}}-\frac{p_p\gamma_1}{p_s}=\beta\left(\gamma_1\right) \tag{21}$$

where $\gamma_3 \sim \exp\left(\zeta_3^l\right)$ and for exponential random variable,

$$\beta\left(\gamma_1\right)>0 \tag{22}$$

$$\frac{\Lambda^{\frac{1}{D}}}{p_s\left(p_p\gamma_1\right)^{\frac{N-D}{D}}}-\frac{p_p\gamma_1}{p_s}>0. \tag{23}$$

After simplifying (23) we will get,

$$\gamma_1<\frac{\Lambda^{\frac{1}{N}}}{p_p}=\alpha(\text{let}). \tag{24}$$

As γ_1 and γ_3 are independent exponential random variable, it's joint probability density function can be represented as $\zeta_1^l e^{-\zeta_1^l\gamma_1}\zeta_3^l e^{-\zeta_3^l\gamma_3}$

$$Pr(\gamma_3<\beta\left(\gamma_1\right))=\int_{\gamma_1=0}^{\alpha}\int_{\gamma_3=0}^{\beta(\gamma_1)}\zeta_1^l e^{-\zeta_1^l\gamma_1}\zeta_3^l e^{-\zeta_3^l\gamma_3}d\gamma_1 d\gamma_3 \tag{25}$$

$$=\int_{\gamma_1=0}^{\alpha}\zeta_1^l e^{-\zeta_1^l\gamma_1}\left(1-e^{-\zeta_3^l\beta(\gamma_1)}\right) \tag{26}$$

$$=1-e^{-\zeta_1^l\alpha}-\zeta_1^l\Upsilon_1 \tag{27}$$

where,

$$\Upsilon_1=\int_{\gamma_1=0}^{\alpha}e^{\left(\delta_2\gamma_1-\frac{\delta_1}{\gamma_1^{\frac{N}{D}-1}}\right)}d\gamma_1 \tag{28}$$

$$\delta_1=\frac{\zeta_3^l\Lambda^{\frac{1}{D}}}{p_s p_p^{\frac{N}{D}-1}},\ \delta_2=\frac{\zeta_3^l p_p}{p_s}-\zeta_1^l \tag{29}$$

Equation (28) is intractable, however, if we substitute, $\delta_2=0$ i.e. $\frac{\zeta_1^l}{\zeta_3^l}=\frac{p_p}{p_s}$, so eq. (28) can be reduced to,

$$\Upsilon_1=\int_{\gamma_1=0}^{\alpha}e^{-\delta_1\gamma_1^{-\left(\frac{N}{D}-1\right)}}d\gamma_1. \tag{30}$$

Let's substitute $\gamma_1^{-\frac{N-D}{D}}=t$. So eq. (30) reduces to,

$$\Upsilon_1=\frac{D}{N-D}\int_{\alpha^{-\frac{N-D}{D}}}^{\infty}t^{-\frac{N}{N-D}}e^{-\delta_1 t}dt. \tag{31}$$

From [13], eq. (31) can be solved as, [1]

$$\Upsilon_1=(-1)^{n+1}\delta_1^n\frac{Ei(-\delta_1 u)}{n!}+\frac{e^{-\delta_1 u}}{u^n}\sum_{k=0}^{n-1}\frac{(-1)^k\delta_1^k u^k}{n(n-1)...(n-k)} \tag{32}$$

[1] However, in this paper we have solved eq. (28) numerically to obtain the theoratical plots.

where, $n = \frac{D}{N-D}$ and $u = \alpha^{-\frac{N-D}{D}}$

Hence from (13),(14),(15),(27) the primary outage probability,

$$P_{out}^{p} = e^{-\frac{\zeta_2^l \sigma^2}{p_p}\rho_1}(1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p}\rho_1}\right)\left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p}\rho_1}\right). \quad (33)$$

3.3 Critical Distance Analysis

If we consider only primary system (i.e. no secondary system exists) then outage probability of the direct link with target rate R_T is given by (6). With proposed scheme, the outage probability of the primary system (with few subcarriers D) should be always less than or equal to the outage probability of direct link. From eq. (6) and (33) we have,

$$P_{out} > P_{out}^{p} \quad (34)$$

For a given target rate, there will be always a critical distance ζ_2^* (distance between PT and ST) above which no spectrum sharing is possible. In other words, if ST is located at or beyond critical distance from PT then primary outage probability with cooperation will always be greater than or equal to direct outage probability even ST would work as a pure relay.

$$1 - e^{\left(-\frac{\sigma_1^2(2^{R_T/N}-1)\zeta_1^l}{p_p}\right)} < e^{-\frac{\zeta_2^l \sigma^2}{p_p}\rho_1}(1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p}\rho_1}\right)\left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p}\rho_1}\right) \quad (35)$$

From eq. (35)

$$\zeta_2^* = \left[\frac{p_p}{\rho_1 \sigma^2} ln\left(\frac{\Phi_1 - \Phi_2}{\Phi_3 - \Phi_2}\right)\right]^{\frac{1}{l}} \quad (36)$$

where $\Phi_1 = 1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1$, $\Phi_2 = \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p}\rho_1}\right)$ and $\Phi_3 = 1 - e^{\left(-\frac{\sigma_1^2(2^{R_T/N}-1)\zeta_1^l}{p_p}\right)}$.

From eq. (36), the critical distance ζ_2^* for different target rates can be calculated. The critical distances for some of the predefined target rates with $p_p = 10$ dB, $p_s = 30$ dB and best possible value of D *i.e.* (D=N=32) has been given in table I.

Table 1.

R_T	8	16	32	64
ζ_2^*	3.4	2.68	1.92	1.12

3.4 Secondary Outage Probability

In phase II of transmission ST will transmit N-D subcarriers to SR via $\Psi_{4,k}$ link. The instantaneous rate is given by,

$$R_S = \frac{1}{2}\sum_{k=1}^{N-D} \log_2\left(1 + \frac{p_{s,k}\gamma_{4,k}}{\sigma_4^2}\right). \quad (37)$$

Let's assume that all subcarriers comprise same power $p_{s,1} = p_{s,2} = p_{s,N} = p_p$ and channel coefficients of all subcarriers are same for one OFDM symbol $\gamma_{4,1} = \gamma_{4,2} = \gamma_{4,N} = \gamma_4$. Equation (37) can be deduced as,

$$R_S = \frac{1}{2}(N-D)\log_2\left(1+\frac{p_s\gamma_4}{\sigma_4^2}\right). \quad (38)$$

Let the target rate for secondary system is defined as R_{Ts}. Outage occur if $Pr(R_S < R_{T_s})$

$$Pr(R_S < R_{T_s}) = Pr\left(\gamma_4 < \frac{\rho_2\sigma_4^2}{p_s}\right) = 1 - e^{-\frac{\zeta_4^l\sigma_4^2}{p_s}\rho_2} \quad (39)$$

where $\gamma_4 \sim \exp\left(\zeta_4^l\right)$ and $\rho_2 = 2^{\frac{2R_{T_s}}{N-D}} - 1$

4 Simulation Results & Discussion

We have done simulation for the outage probability with respect to number of subcarriers under specified settings. For the ease of analysis, PT, PR, ST & SR are considered to be collinear. PT is located at distance (0,0) in two dimensional plane while PR is located at (1,0) *i.e.* $\zeta_1 = 1$. SR lies in between PT and PR at coordinates (0.75,0) and ST moves along the X axis. Theoretical and simulation results of the outage probability for $\zeta_2 = 0.5, \zeta_2 = 1.2$ & $\zeta_2 = 1.92$ with respect to number of relayed subcarriers D are given. we have chosen target rate $\mathrm{R_T} = \mathrm{N} = 32$ and subcarrier power $\mathrm{p_p} = 10\mathrm{dB}, \mathrm{p_s} = 30\mathrm{dB}$. The path loss exponent has set to be $l = 4$.

Figure 2 shows the theoretical and simulation result of the outage probability

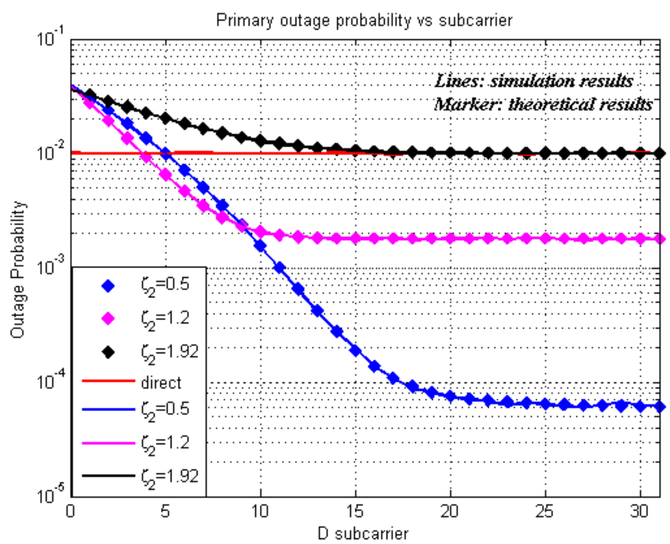

Fig. 2. Primary outage probability vs subcarriers

of the primary system vs number of subcarrier required for cooperation. Theoretical results are strongly following the simulated one. From figure 2 we can see that as number of forwarded subcarriers D from ST to PR increases, the outage probability decreases. For $\zeta_2 = 0.5$, and $\mathrm{D} > 5$ the outage probability with cooperation is less than the direct transmission. Hence with this given power and target rate profile, if ST will forward only 5 subcarriers to PR then outage probability with cooperation will be less than the outage probability with direct tranmission. So secondary system has opportunity to do spectrum access of licensed primary band to transmit its own data to secondary receiver. With this protocol out of total given N=32 subcarriers, the remaining N − D subcarriers can be used by ST to do opportunistic spectrum access. For higher values of D it is quite obvious that primary outage probability will reduce as providing more subcarriers for the relaying of primary signal & less subcarriers used for the secondary system transmission. However for D > 20, the outage probability gets stagnant. This is due to the fact that when D approaches it's maximum value, the outage probability with MRC $Pr\left(R_{PR}^{MRC}\right)$ attains very small value and the decoding of primary signal at ST becomes the only limiting factor for outage probability i.e $Pr(R_N^{Pt-St} < R_T)Pr(\frac{1}{2}R_N < R_T)$. Thus further increasing D will not impact primary outage probability.

For $\zeta_2 = 1.2$, distance between PT→ST increases but distance between ST→PR decreases i.e. $\zeta_3 = 0.2$. Therefore for small value of D, the outage probability is less than previous case, here only 4 subcarriers are required to achieve same outage probability as direct transmission. But for D > 10, the outage probabilty is constant. This happens because of high distance between PT and ST, no further successful decoding of primary signal occur at ST. For $\zeta = 1.92$ (critical distance), no opportunistic spectrum access is possible, as outage probability with cooperation is always higher than direct transmission. Figure 3 shows the

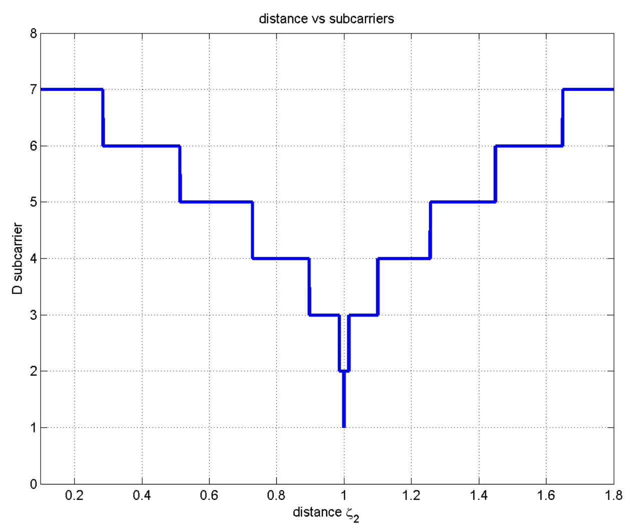

Fig. 3. Subcarriers vs ζ_2

relationship between D and ζ_2 for $R_T = 32$. From figure 3 we can find the exact number of subcarriers D forwarded via ST to PR, when outage probability of proposed cooperation scheme would be less than direct transmission. At $\zeta_2 = 0.1$ distance between PT-ST is 0.1 consequently distance between ST-PR will be 0.9, therefore ST would required to forward minimum 7 subcarriers to PR to achieve the performance better than direct transmission. As the value of ζ_2 increases from $0.1 < \zeta_2 < 1$, distance between ST-PR will decreases, so required number of subcarriers i.e. D will also decreases. However for $\zeta_2 > 1$, ST is moving away from PR, therefore value of D increases with ζ_2. Figure 4 shows the 2-D graph

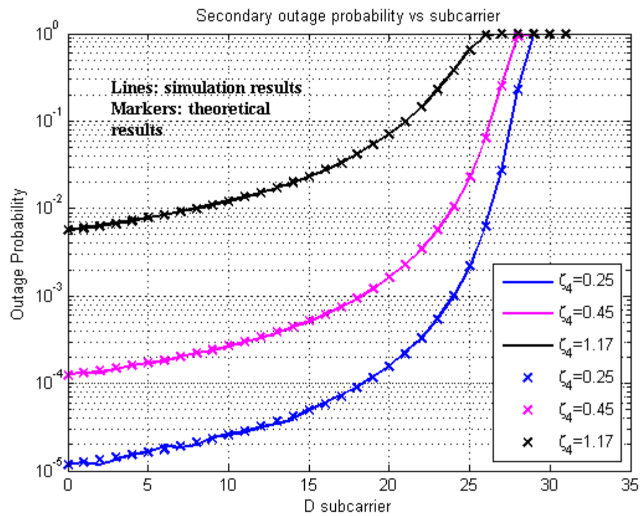

Fig. 4. Secondary outage probability vs subcarriers

of secondary system outage probability for $\zeta_4 = 0.25$, $\zeta_4 = 0.45$ & $\zeta_4 = 1.17$ w.r.t D subcarriers relaying via ST to primary receiver. For simulation collinear distance model has taken with $\frac{p_s}{\sigma_4^2} = 30\text{dB}$ & $R_{T_s} = 32$. From the graph we can clearly see that for some small value of D, the value of N-D will be high, therefore the outage probability of secondary (cognitive) system is low. As the numbers of subcarriers relaying to primary receiver via ST increases then the subcarriers forwarded to SR i.e. N-D will decrease, consequently the outage probability of the secondary system increases. At $10 < D < 32$ (when primary outage probability with cooperation is less than direct transmission), the secondary outage probability is significantly small. Hence very good opportunistic spectrum access is possible with the proposed protocol. At very high value of D, when ST behaves like a pure relay (forwarded all primary subcarriers to PR), then $N - D = 0$ and there will be no secondary communication possible and hence outage probability will be very high (approx=1).

5 Conclusion

In this paper, secondary system gains opportunistic spectrum access by assisting the primary system to achieve its target rate. Secondary transmitter acts as a DF relay to help the primary system by relaying few subcarriers to primary receiver to fulfill the required target rate of primary system while remaining subcarriers can be used for secondary transmission. There is a critical distance between PT and ST, if ST is located at or beyond critical distance from PT then there will be no opportunistic spectrum sharing. We have shown that depending on the distance between PT and ST, it is possible to find exact number of subcarriers that should be forwarded by ST to PR for outage probability with cooperation to be less than direct transmission.

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